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A COMPARISON OF THE LOCATION REFINEMENT TECHNIQUES IN THE SDAC/LASA EVENT PROCESSOR

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This report shows that the number of events reportable on the SDAC/LASA Daily Summary could be increased 15 to 20 percent by lowering the EP acceptance threshold from 14db to 12db. When operating the EP with S/N acceptance threshold of 10db, beampacking increases the number of verified events on the Daily Summary by approximately 30 - 40 percent over the number produced by crosscorrelation.

A COMPARISON OF THE LOCATION REFINEMENT TECHNIQUES
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INTRODUCTION

The SDAC/LASA system is comprised of a Detection Processor (DP) and an Event Processor (EP) (Dean, et al., 1971). In the DP a set of array beams is deployed in a fixed pattern to cover the Earth. The detection process selects the beam with the maximum signal power, and the coordinates of this beam along with the arrival time are passed to the EP for location refinement and event characterization.

There are two location refinement techniques programmed into the EP. The primary method, crosscorrelation, starts with the location from the DP and successively crosscorrelates the signal waveform recorded at each subarray with the signal waveform on the beam formed from the remainder of the full array. The secondary method, beampacking, also starts with the DP location but focuses 18 additional fixed beams around it. The revised location is that of the beam with the largest signal. Beampacking was programmed to be used only when the crosscorrelation method failed from a lack of signal power.

Since EP uses one of these two location refinement techniques on every signal it analyzes, we are interested in comparing the two for location accuracy (the standards for location accuracy and magnitude are World-wide network located events). Moreover, crosscorrelation which requires more computer time than beampacking is able to process fewer events per day.

Hence, it must operate with a higher signal-to-noise (S/N) threshold so that the EP can stay abreast with the rate of detections.

This report describes three experiments associated with these location refinement techniques. The first experiment compares the location accuracy of the two methods and the computer time required by each in the current system. In the second experiment, the normal EP operating threshold of 14db for S/N was lowered to 12db. The objectives were to estimate how many additional events would be added to the LASA Daily Summary, to determine which location refinement technique operated more reliably at the lower S/N threshold, and to estimate how much computer time was required for each. In the third experiment, the normal EP threshold of 14db was lowered to 10db, which has been the DP operating threshold since 1971. The objectives were to estimate whether the EP computer-analyst team could stay abreast of this DP detection rate using beampacking, and to estimate how many additional events would be added to the LASA Daily Summary at the 10db EP threshold.

EXPERIMENT ONE: COMPARISON OF LOCATION REFINEMENT TECHNIQUES USED IN THE SDAC/LASA EVENT PROCESSOR

The first experiment is an off-line test of the two location refinement methods. We are interested in the comparative merits of the two methods:

1) do they have equal signal-to-noise ratio thresholds?
2) how do the locations obtained by each method compare to locations obtained by world-wide networks?
3) do the estimates of event magnitude differ appreciably?
4) what are the weaknesses of each method? and
5) is there a significant difference in the computer processing time required for each?

THE ALGORITHMS

Crosscorrelation

The crosscorrelation (CC) algorithm works as follows: Initially, subarray beams are formed for all 21 LASA subarrays aimed at the location listed by the Detection Processor (DP). Then a partial array beam is formed aimed at the DP location using all except one subarray beam and using the appropriate delays including region corrections based on the observed travel-time anomalies as defined by Chiburis (1966). The individual subarray beam is then crosscorrelated with the partial array beam and shifted in time until a maximum correlation is obtained (the maximum number of lead/lags allowed is 17 on the first iteration and

seven on each subsequent iteration). A new partial array beam is then formed which includes the correlated subarray beam but excludes one of the other subarray beams. The excluded subarray beam is crosscorrelated with the new partial array beam in like manner, as are each of the other subarray beams in turn. The entire process is iterated until there is no improvement in signal power on the array beam. The final relative shifts of each subarray beam are then used to compute in a least-squares sense the velocity and azimuth of the signal as it crossed the array, assuming a plane wave mode of propagation. An epicenter can be estimated using a seismic P wave earth model. The EP system uses the velocity tables of Herrin (1968).

Beampacking

In the beampacking (BP) algorithm, the first step is to form an array beam aimed at the location listed by the DP. Eighteen more array beams are then formed to build a hexagonal grid (Figure 1) (with a constant beam separation in inverse velocity space) around the initial beam location. Again the Herrin 1968 model is used with region corrections to generate the array beams. The array beam with the maximum signal power is selected as having the location of the event.

This process must also be iterative, however, because a grid where r is large enough to be certain of containing the beam with maximum signal power will not yield an acceptably precise location. Hence, if

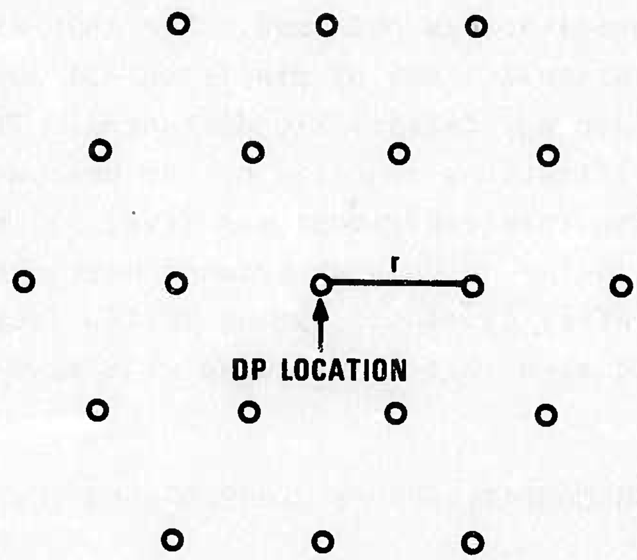

Figure 1. The beam deployment pattern used by the Beampacking algorithm in inverse velocity space.

the selected beam is in the outer ring of the grid, a new grid is formed centered around it. The process is repeated until the maximum power occurs on an inner beam. The grid spacing, r, is then reduced by a factor of two and the process repeated until a desired limit of precision is obtained. For this experiment, the computational limit of precision was approximately 75 km for average teleseismic distances. The average number of iterations required by the beampacking algorithm in this experiment was five. It should be noted that prior to this experiment beampacking was used only after crosscorrelation failed from 'lack of power', and also that beampacking will always yield a solution.

PERFORMANCE COMPARISONS OF CROSSCORRELATION AND BEAMPACKING

Data Base

The data base for this experiment consists of 44 EP events occurring during the first nineteen hours (GMT) of February 15, 1972. Nineteen of the events were eventually verified by World-wide seismic networks. The data base was run through the off-line EP program (similar to on-line but usable in an off-line mode of operation) using the beampacking location refinement algorithm. The off-line results were then compared to the on-line results where the crosscorrelation algorithm was used primarily. Both sets of results were compared to World-wide network results. These comparisons are discussed below.

S/N Threshold

Of the 44 EP events, 27 were successfully processed by the crosscorrelation algorithm. The other seventeen were located by beampacking after crosscorrelation failed. The EP threshold was set arbitrarily at a S/N threshold of 5/1 (14db) as measured by the DP. Figure 2a shows the frequency of occurrence of the EP events with respect to the DP S/N (db) in both discrete and cumulative form. Figure 2b shows in a similar manner the frequency of occurrence for the verified events only. From Figure 2a it is obvious that beampacking works to a lower S/N threshold than does crosscorrelation. And Figure 2b shows that at least some of the events with smaller S/N's are real. Indeed, 36 percent of the verified events in this sample were added by beampacking after crosscorrelation had failed. Three of the nonverified events are core phases, probably PKP's.

Location Accuracy

Table I lists the nineteen confirmed events with the locations obtained by both crosscorrelation and beampacking. Also included, in columns titled DP, CC, and BP respectively, are the location errors as compared to World-wide network locations for the DP output, the location errors obtained when using the crosscorrelation algorithm, and the location errors obtained when using the beampacking algorithm. Crosscorrelation failed totally or finished with a significantly greater

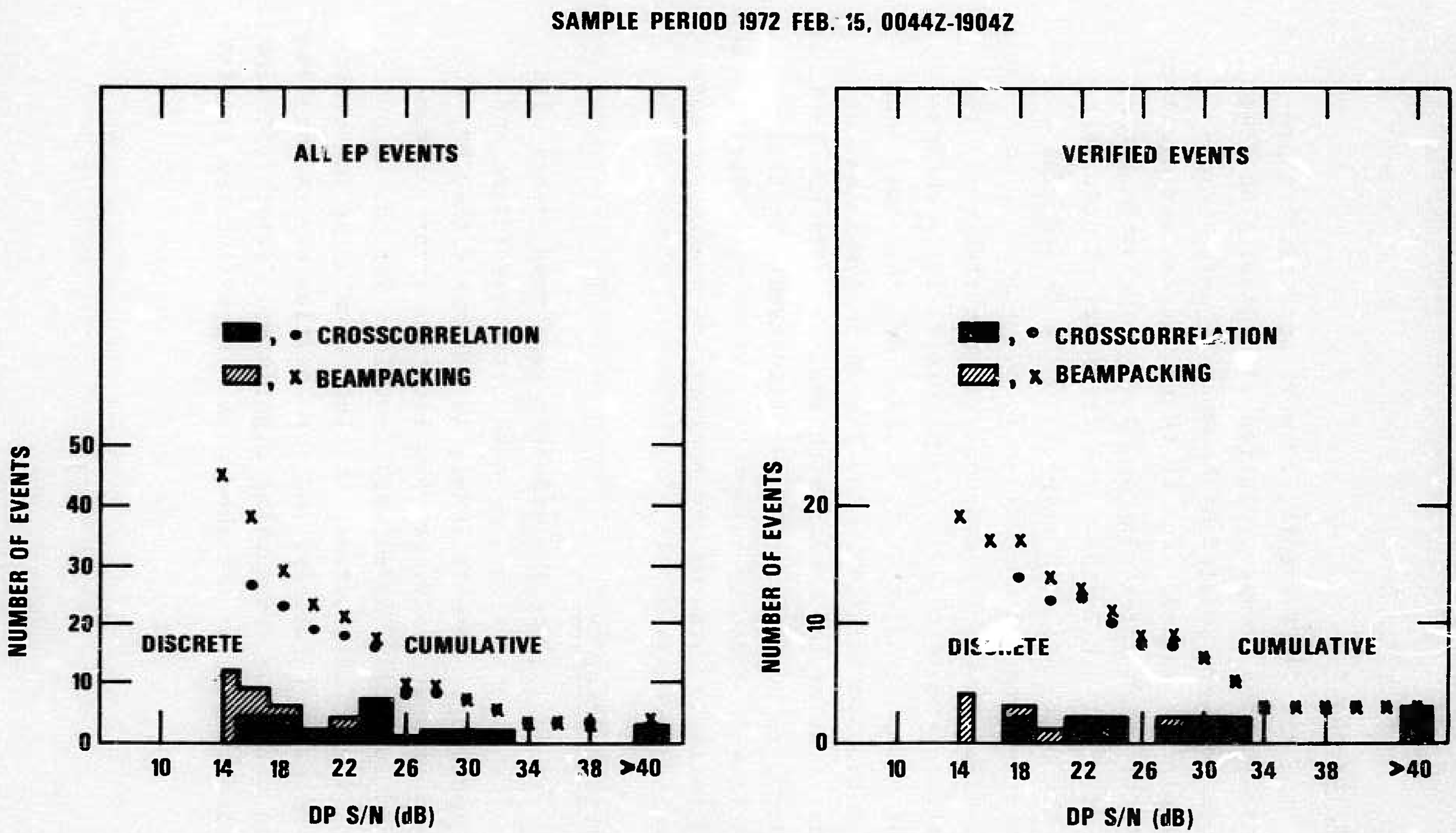

Figure 2a,b. Number of events processed to solution by Crosscorrelation and by Beampacking as a function of the DP estimate of S/N (experiment one).

TABLE I

List of Confirmed SDAC/LASA Events with the EP Locations and Location Errors as Compared to World-Wide-Network Locations (Experiment 1).

Arrival Time *	SDAC Geographic Location	Cross-Correlation Lat.	Cross-Correlation Long.	Beampacking Lat.	Beampacking Long	SDAC m_b	Distance (Deg)	Location Error (KM) DP	Location Error (KM) CC	Location Error (KM) BP	DP S/N
004425.0	Solomon Islands	--	--	8.4S	162.1E	4.9	97	505	--	645	5.4:1
030659.6	Rat Islands	52.4N	175.4E	52.8N	175.1E	4.5	50	300	155	145	30.6:1
042141.0	Tonga Islands	15.8S	173.5W	15.7S	173.6W	4.9	87	245	20	15	118.1:1
051621.6	Kurile Islands	42.7N	147.6E	43.3N	148.2E	3.8	68	210	145	65	16.4:1
061247.4	Honshu, Japan	39.1N	140.7E	39.0N	141.1E	3.9	75	605	50	55	13.9:1
071903.0	Samoa Islands	15.3S	171.9W	15.7S	172.2W	4.4	85	830	35	45	29.8:1
084834.8	Mediterranean Sea	--	--	36.0N	21.6E	3.9	88	785	--	430	9.2:1
084838.4	Hokkaido, Japan	32.1N	135.1E	41.8N	139.4E	3.9	74	480	1275	230	8.6:1
090531.8	Northern Colombia	6.2N	72.4W	6.8N	72.4W	5.3	49	505	95	65	113.6:1
095300.6	Bonin Islands	28.7N	141.0E	28.2N	140.6E	3.7	86	270	325	285	7.4:1
101333.6	Coast Honshu, Japan	--	--	38.0N	142.3E	4.5	75	340	--	130	5.0:1
101403.0	Veru Cruz	--	--	18.1N	95.3W	3.9	35	90	--	545	27.0:1
104045.6	Kurile Islands	--	--	44.5N	147.6E	3.3	69	185	--	85	7.9:1
113005.4	Andreanof Islands	51.3N	177.3W	51.5N	178.3W	5.3	45	60	15	65	116.0:1
124631.2	Greece	38.1N	23.7E	37.7N	25.0E	3.8	85	180	115	110	24.7:1
143626.4	Azores Islands	39.2N	31.4W	39.0N	31.2W	4.4	53	150	35	60	37.6:1
165604.8	Kurile Islands	44.8N	152.5E	43.7N	151.6E	4.1	64	130	135	280	17.6:1
181658.5	Nicaragua	4.3N	82.1W	11.7N	87.1W	4.4	39	100	865	135	43.6:1
184639.3	Greenland Sea	75.5N	47.7W	77.1N	9.0W	3.7	52	1220	1615	615	12.4:1
			Average location error for all 19 Events					380	**	210	
			Standard Deviation					305		205	
			Average location error for 14 Events					380	350	155	
			Standard Deviation					325	515	160	

* All events are on 1972 February 15.

** Crosscorrelation did not locate all 19 of the confirmed events.

location error than the initial DP location on nine of the nineteen events. Beampacking worsened three of the locations and improved on the detection location on thirteen. Crosscorrelation improved on nine locations. Of the fourteen events located by both methods, beampacking showed a smaller location error than crosscorrelation on nine. The average location errors for the fourteen common events are 350 km for crosscorrelation and 155 km for beampacking. Thus, on the average, beampacking did better by a factor of 2.3 over crosscorrelation. Furthermore, for those events it did process, crosscorrelation only improved on the DP location a factor of 1.1 on the average. The Solomon Island event at 97° distance from LAO is approaching the P shadow zone and probably should not be included in the averages. The average error for beampacking for all 18 of the other events is 185 km.

It should be noted that, even for the larger events, the crosscorrelation locations are not more reliable (the Nicaraguan event was mislocated over 800 km). The Mediterranean Sea event (S/N = 9.2:1) was processed to completion by crosscorrelation but was mislocated by more than 3500 km and out of the P range. Because of this error, the result was not used in determining the average location error for crosscorrelation. The failure of crosscorrelation may have been due to the fact that this event was crossing the array at the same time as the Hokkaido event.

Signal Size

Based on this limited sample, there is no apparent difference, on the average, in the magnitudes measured on the array beam generated by beampacking as compared to the array beam generated by crosscorrelation. Only one event showed a difference in the Log_{10} A/T (amplitude/period) as great as 0.06 units. However, as this event (0516z) was only one millimicron (0-peak), the waveform was probably distorted by background noise. Beampacking led to the smaller value even though it had the smaller location error for this event by more than a factor of two.

Weaknesses of Each Method

Crosscorrelation attempts to align the most coherent waveform within a window around the detection time. On weak or incoherent event waveforms (low S/N or signals that change character within the space of LASA), the process yields a set of delays which may or may not correspond to a reasonable earth model. This is graphically illustrated with the two intermixed signals at 0848z. Figures 3, 4, 5, and 6 show the beamed data traces obtained by crosscorrelation and beampacking for the two events. As can be seen in Figure 3, the beam amplitude for crosscorrelation is greater than on the beampacked array beam of Figure 4. However, the crosscorrelation beam is aimed over 1200 km off the true location, whereas beampacking is off by only 230 km. The same type of comparison can be made for

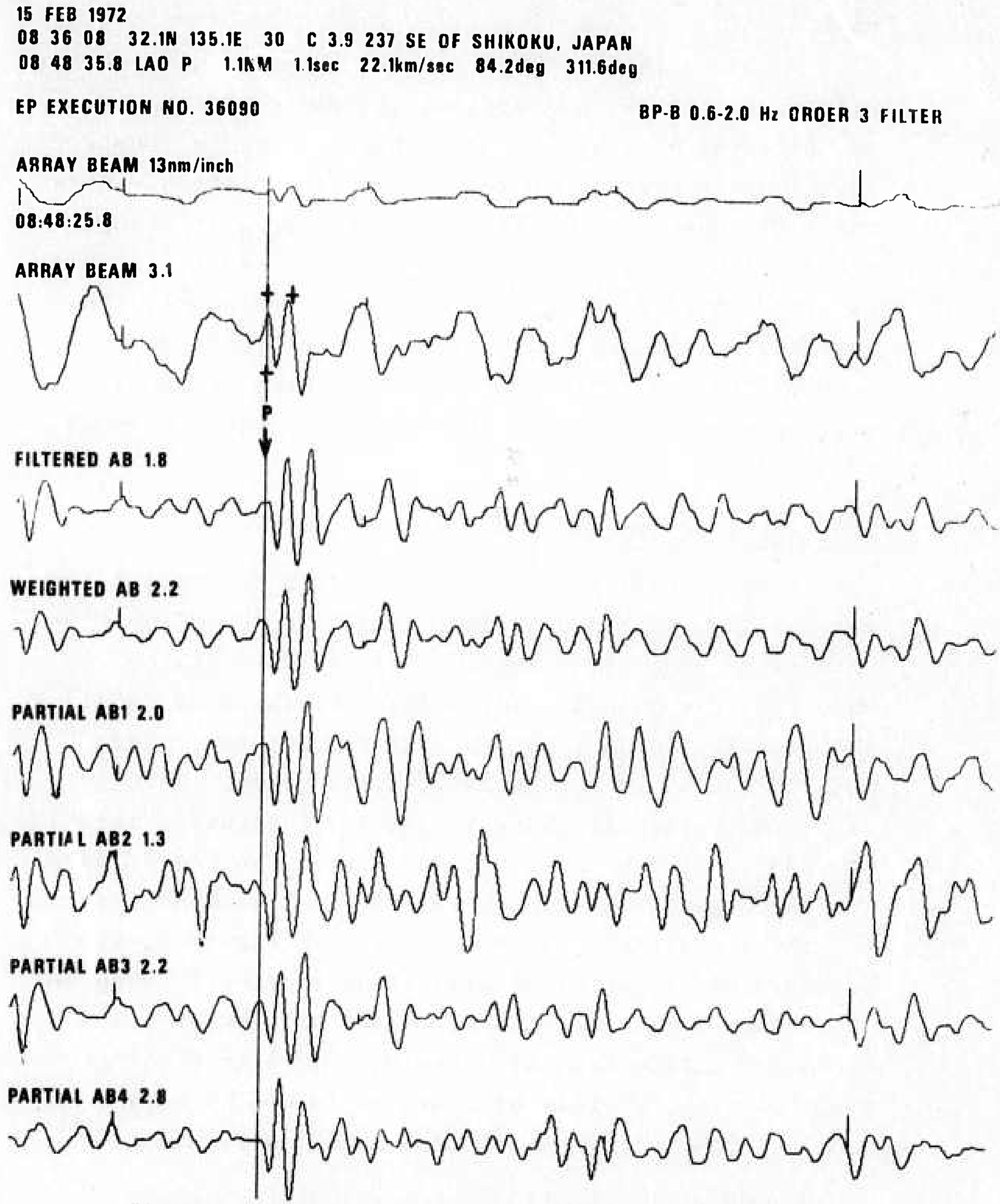

Figure 3. Example of a mis-aimed beam by Crosscorrelation with greater signal amplitude than the corresponding correctly aimed beam by Beampacking (see Figure 4).

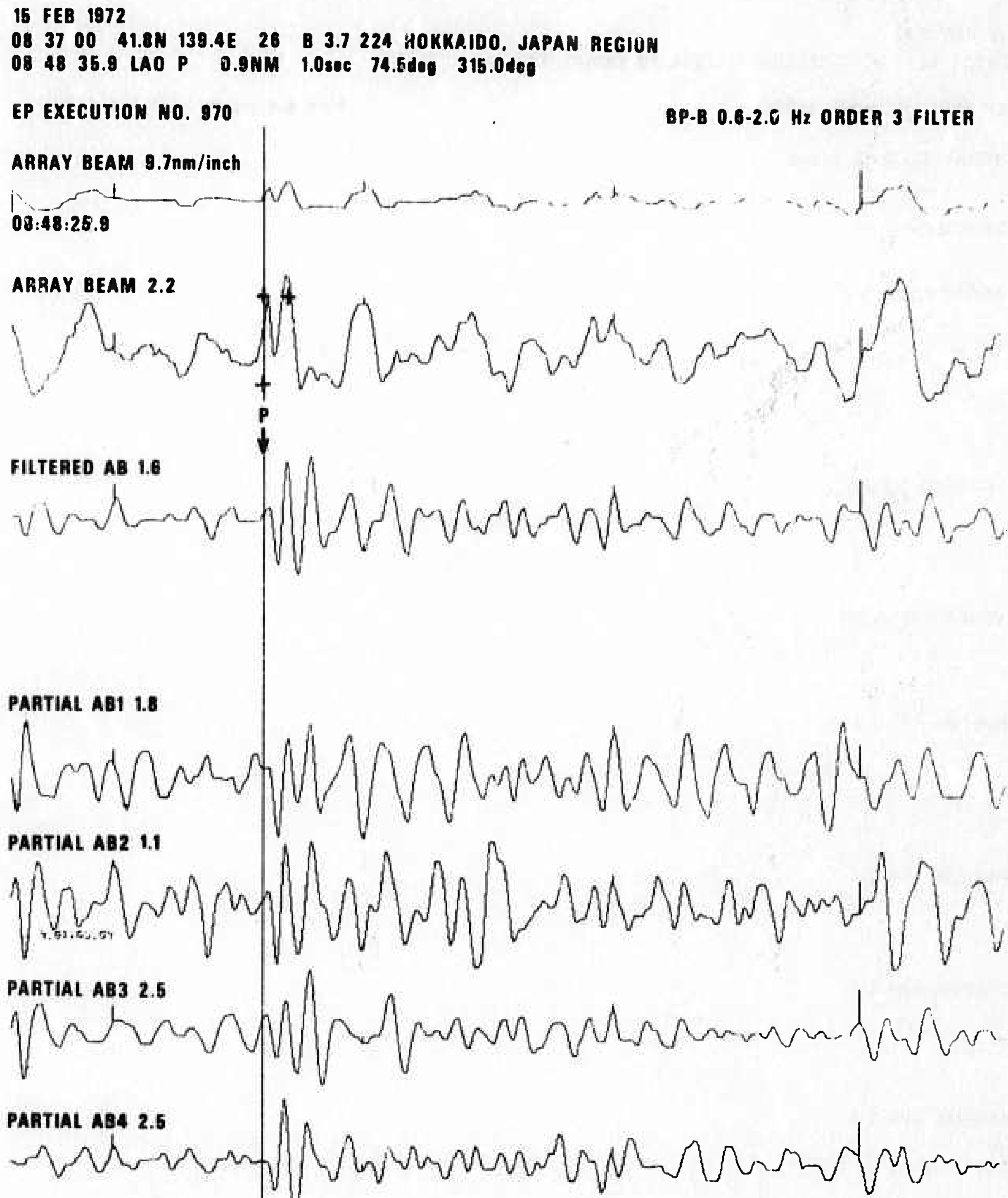

Figure 4. Properly aimed beam for Hokkaido event.

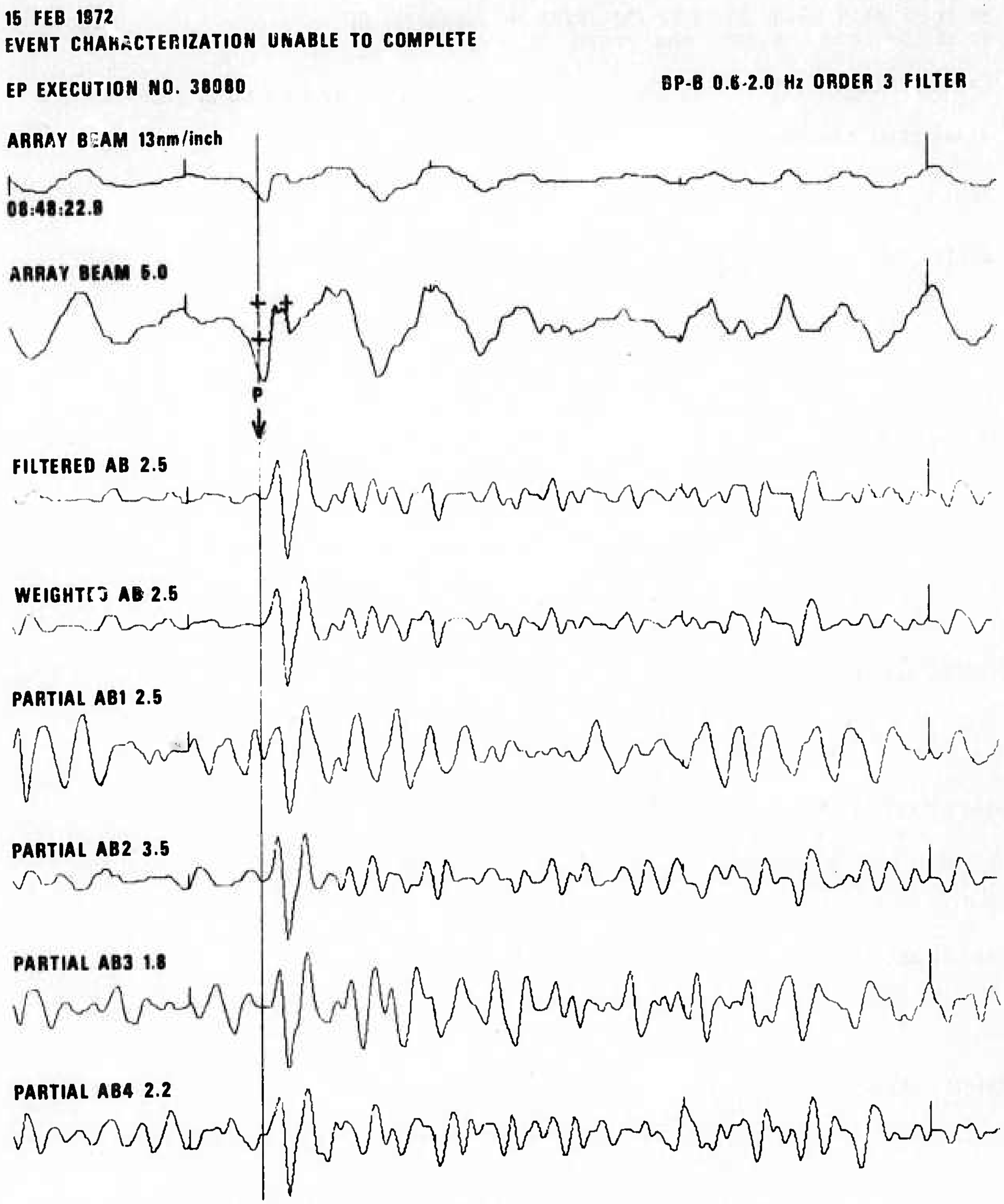

Figure 5. Example of mis-aimed beam by Crosscorrelation with greater signal amplitude than the corresponding correctly aimed beam by Beampacking (see Figure 6).

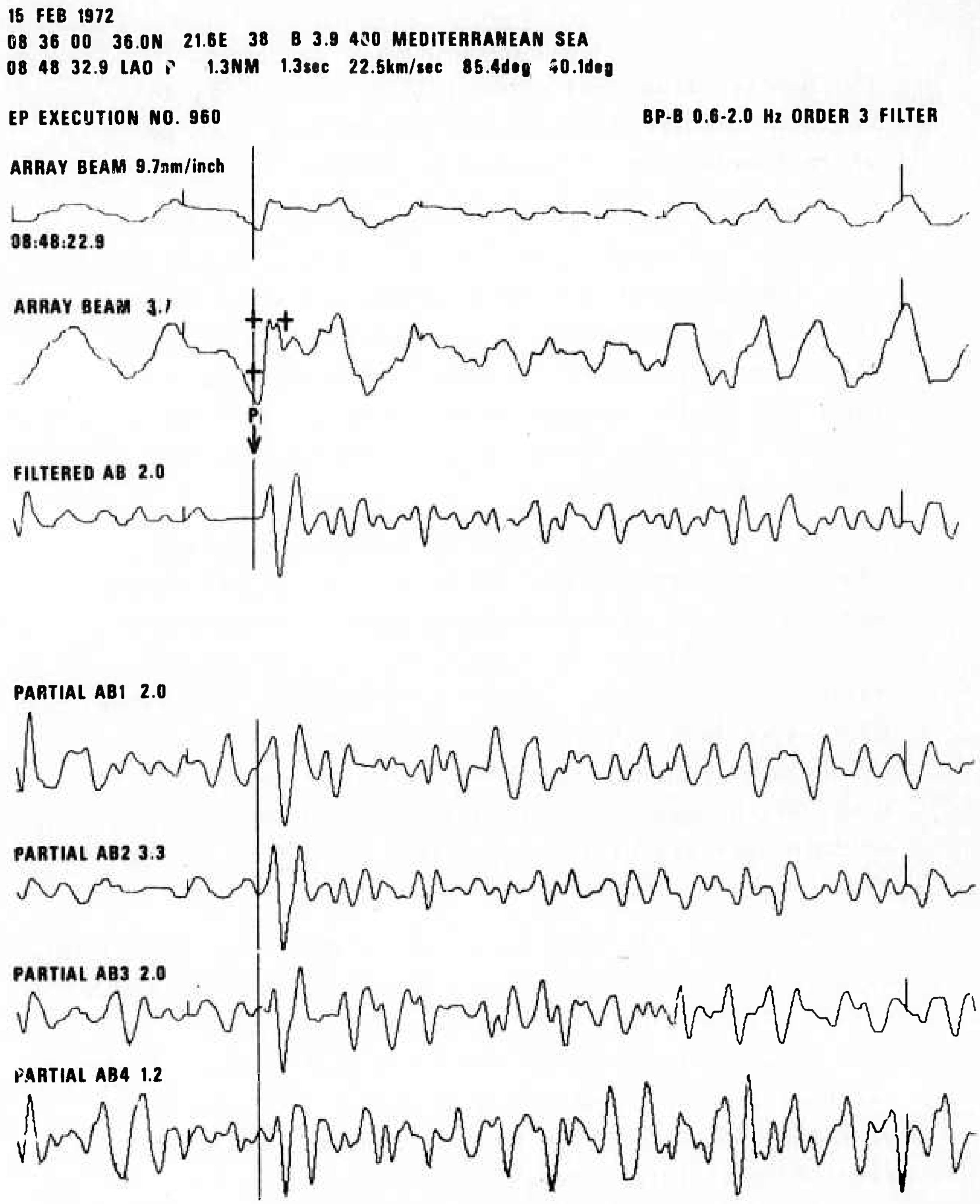

Figure 6. Properly aimed beam for Mediterranean Sea Event.

the Mediterranean Sea event (Figures 5 and 6), for which crosscorrelation mislocated by over 3500 km while beampacking mislocated by 430 km.

Because the crosscorrelation process aligns the most coherent waveform within the window, signal or not, the magnitude estimates of low S/N events where the subarray alignment cannot readily be verified by visual analysis must be suspect. The previously mentioned Kurile Islands event, with the magnitude disparity, and the Hokkaido and Mediterranean Sea events are examples.

However, in spite of these shortcomings, the crosscorrelation process gives the best signal alignment for events with reasonably coherent signal waveforms across the array, especially when the proper region corrections are unknown. The delays generated by crosscorrelation are ideally suited for use in a standard Geiger least-squares solution which jointly uses the changing velocity across the array and the azimuth aperture of the array in arriving at a location.

The principal weakness of the beampacking algorithm is that it is more sensitive to a poorly defined earth model. If the model used is not properly calibrated with regionally dependent travel-time anomalies (Chiburis, 1971), then the peak energy over the beampacking grid will not be well defined and may have a sidelobe peak large enough to trap the iterative

process. Each event in Table I with a beampacking location error greater than 500 km occurred in a region where the corrections are not well defined in the system. An entirely new set of region corrections is being determined as of this writing (Chiburis and Ahner, 1973).

Processing Time

The Central Processing Unit (CPU) time required for the on-line run where crosscorrelation was iteratively used for 27 of the events and at least once for the other 17 was slightly over four and one half hours. The off-line run, using beampacking, required just under three hours CPU time for the location refinement process; a processing time reduction of 35 percent. Beampacking does not, however, utilize the CPU as efficiently as crosscorrelation does and hence the total expected computer time savings is somewhat less than 35 percent.

It should also be noted that the location refinement process is only part of the processing load. The on-line Event Processor has subsequently been run using beampacking only, during which the total 360/40 time required for EP dropped from fifteen hours per day to thirteen hours, an actual savings of thirteen percent. However, this savings allowed a scheduling change which further decreased the daily time requirement to nine hours per day, an ultimate savings of 40 percent. The schedule change involves using the computer and

analysts once a day rather than two or three times. The increased efficiency allows the EP to remain down during the non-used fifteen hours and still be able to catch up before various queues overflow. (If the queues are allowed to overflow, additional work is required to recover the lost data.)

EXPERIMENT TWO: LOWERING OF THE ON-LINE EP S/N THRESHOLD FROM 14db TO 12db

The second experiment is an on-line test where the EP S/N acceptance threshold was lowered from 14db to 12db to see if the system could handle the increased load and to see if there are any events between 12 and 14db good enough to add to the SDAC/LASA Daily Summary. The experiment was run from April 10, 2110Z through April 14, 1026Z, 1972 a period of 85.27 hours (3.55 days).

During this time DP reported 1855 detections operating with a S/N threshold of 10db. EP rejected 1353 of these in its detection log-reduction process where it determines which detections to process. The four principal criteria that EP applies are:

1) A basic S/N threshold below which it will not accept any detection,
2) A priority thresholding scheme whereby detections having velocities beyond the P range have to meet a higher S/N criterion dependent upon the work load in the system,
3) Detections following other detections within a short period of time (tens of seconds) and from the same place as the earlier detection are eliminated as coda detections, and
4) Detections which are listed for each of the two detection beam deployment sets are processed only once with the duplicates being omitted.

The breakdown of the detections rejected by EP follows: 1) below its 12db threshold (44%), 2) duplicate detections (10%), 3) coda detections (11%), and 4) detections having apparent velocities inconsistant with the Herrin P wave earth model (6%). Examples of the types of detections referred to under 4) are high velocity detections from core phases or detections from sidelobes of other detections. The other 502 detections (141 per day) were processed by EP as valid events. For comparison, the number of EP events at a threshold of 14db would have been 249 (70 per day).

The EP events are further subject to the scrutiny of a trained analyst who performs a culling and editing process. The reasons he will cull an event are principally: 1) recognizing that the detection is from the sidelobe of a previously identified event, 2) concluding that the subarrays are not sufficiently well aligned to yield an acceptable location as determined by visual analysis or, 3) observing that the detection is a glitch in the system such as a spike, data dropout, or bad digital data. Of the 502 detections above 12db, 126 (35 per day) were acceptable to the analyst for inclusion in the Daily Summary. At 14db, the corresponding number is 30 per day. Thus by changing the S/N threshold from 14db to 12db, the number of events on the Daily Summary increased 17 percent during this test period. Figure 7 is an example of an event added by lowering the threshold. The detection S/N for this event was 4.4:1 (12.9db). Of course, not all

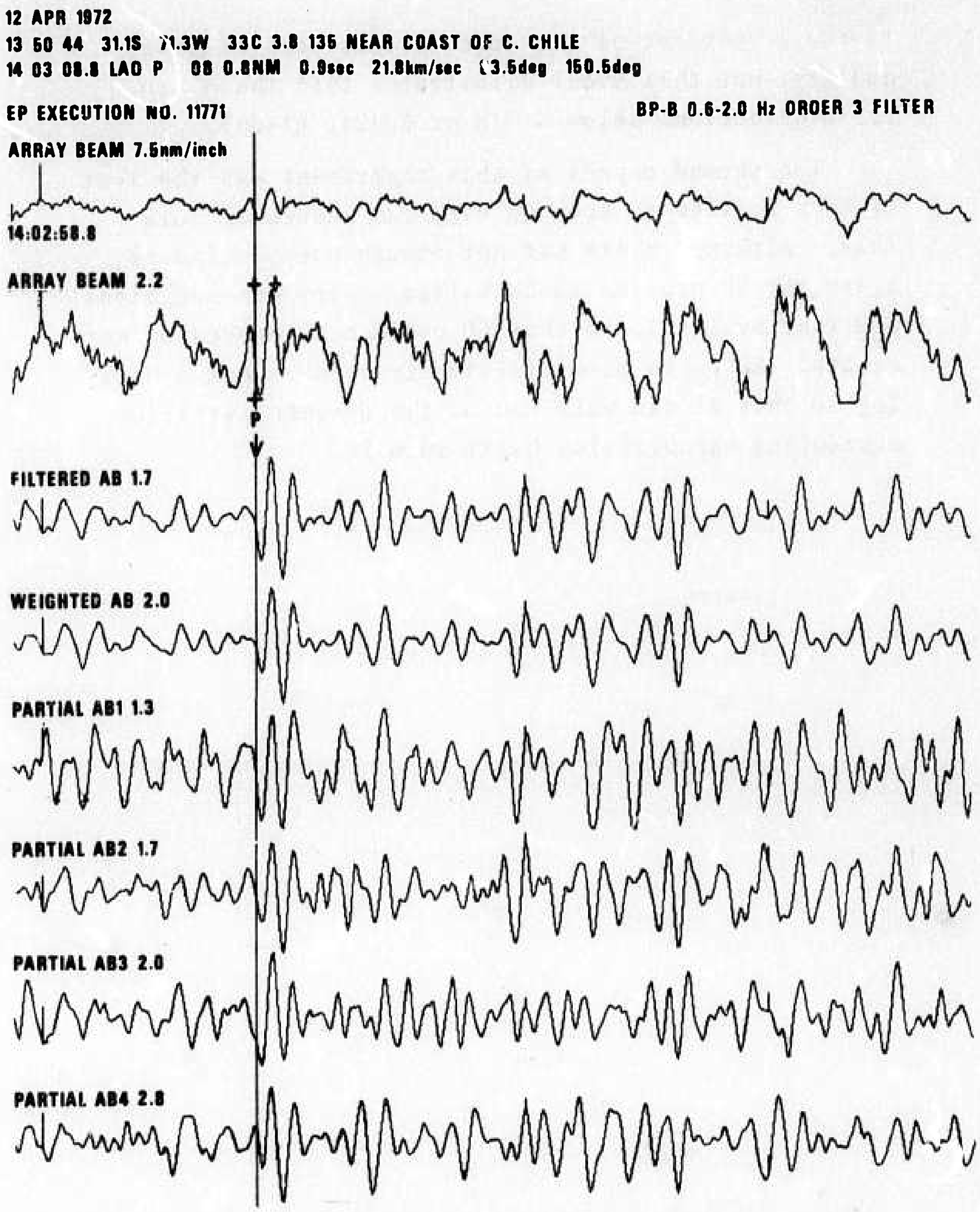

Figure 7. Example of an event detected with a 12.9db S/N (4.4:1).

of the 17 percent of the added events were of this quality, but this event illustrates that there are valid detections below a S/N of 5.02:1 (14db).

The second aspect of this experiment was the test of EP's ability to keep up with the increased work load. Although there was not enough unused time to allow the EP program to be halted, there was additional CPU time available so that EP could have processed more events. EP works more efficiently when it has a backlog so that it can make use of the dynamic partition scheduling capabilities built into it.

EXPERIMENT THREE: LOWERING THE EP S/N THRESHOLD FROM 14db TO 10db AND CHANGING TO BEAMPACKING AS THE PRIMARY MEANS OF LOCATION REFINEMENT

PROCEDURE

On May 22, 1972 at 1720Z, the acceptance S/N threshold of the EP was lowered from 5.02:1 (14db) to 3.16:1 (10db). The EP was operated in this mode until May 23, 1850Z (25.5 hours). Since, as shown in experiment one, the beampacking location refinement algorithm is much faster and achieves a location accuracy at least as good as does crosscorrelation, it was decided to run an on-line test using beampacking as the primary method of location refinement. Hence, at this time we opted to reset the Signal Arrival Queue pointer to May 22, 1720Z and select beampacking as the primary location refinement method. We ran the system under these parameters until May 24, 0456Z (35.6 hours). A discussion of the results follows.

RESULTS

Threshold

A total of 709 detections was listed by DP during the time period of May 22, 1720Z to May 24, 0456Z (1.48 days). The daily rate was 487. This compares to an average rate of 533 detections per day during March, April, and May of 1971 as reported by Dean, et al. (1971). Hence for this time period, the detection rate is somewhat below average.

Of the 709 detections, EP eliminated 307 in its detection-log-reduction process. Table II gives a breakdown of the number of detections that were eliminated at each stage. These results are shown in Figure 8 along with a breakdown of how EP would have worked had it been run at any one of several different basic S/N thresholds. Also shown is the result of the analysts editing and culling process.

The number of events reaching the Summary continues to increase at least down to 10db. This is more clearly illustrated in Figure 9 where both the cumulative and discrete distributions of detections selected for processing by the EP versus S/N are shown. The data presented in Table II are a subset of these data. This particular subset (May 22, 1702Z to May 23, 1850Z) was chosen because only these data were processed by both beampacking and crosscorrelation and it was desired to show the differences in the number of events successfully processed versus S/N for the two methods. It is clear from Figure 9a that beampacking works to a lower S/N threshold than crosscorrelation and from Figure 9b that, 31 percent of the events later verified by World-wide data (9 events) were added by beampacking after crosscorrelation had failed.

Location Accuracy

In this section, we refer to that subset of EP events which occurred between May 22, 1720Z and May 23, 1850Z. During this time period, EP attempted to

TABLE II

Detection Log Reduction Results at an EP S/N Threshold of 10db

Criterion	Number Eliminated	Percent of Previous Total	Number Remaining
Detections	-	-	709
Basic S/N Threshold of 10db	38	5	671
Priority Thresholding	80	12	591
Coda Detections	103	17	488
Duplicated on two Partitions	86	18	402
	307		

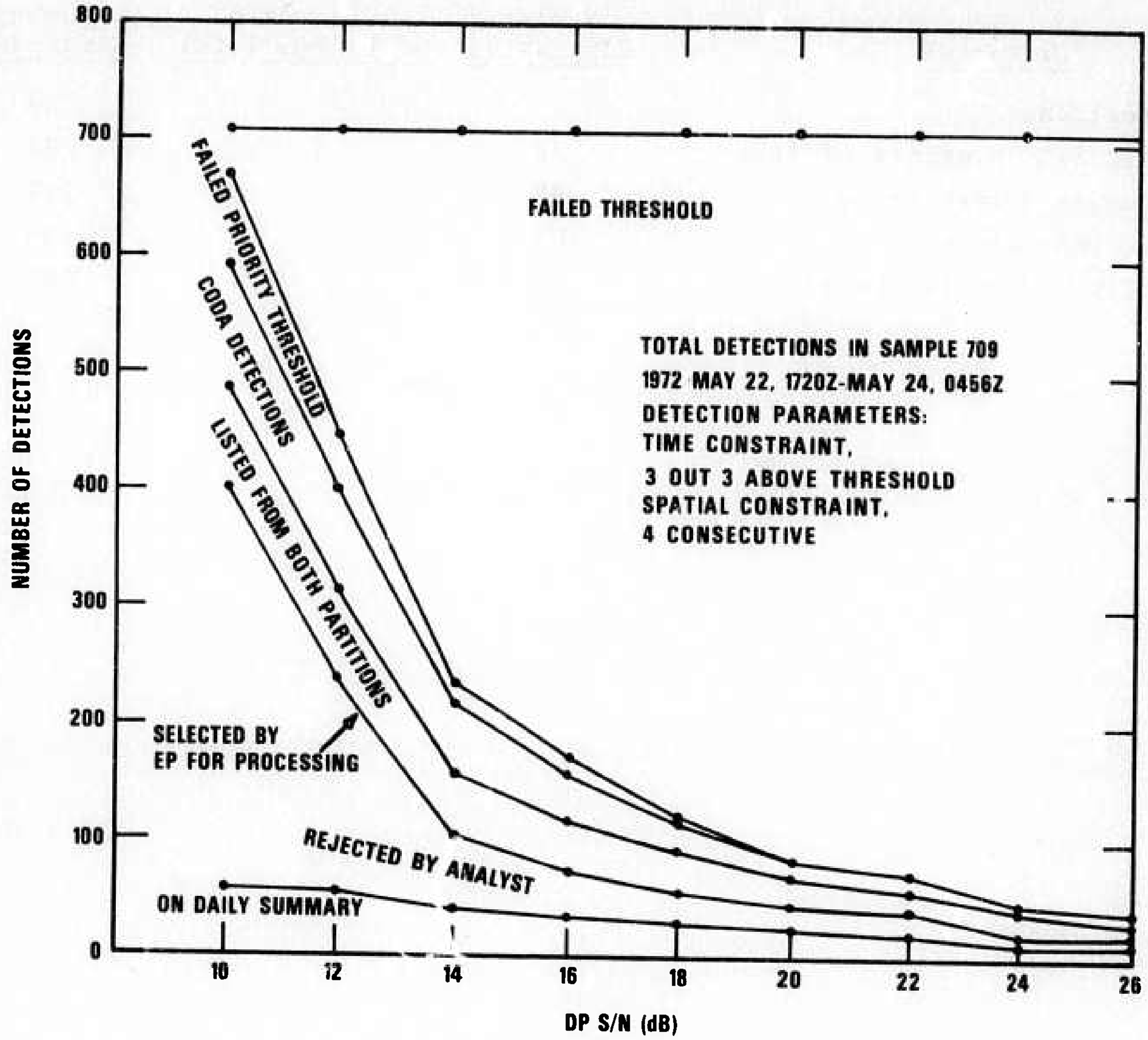

Figure 8. Disposition of detections listed by DP during the 10db experiment and as projected for other S/N thresholds.

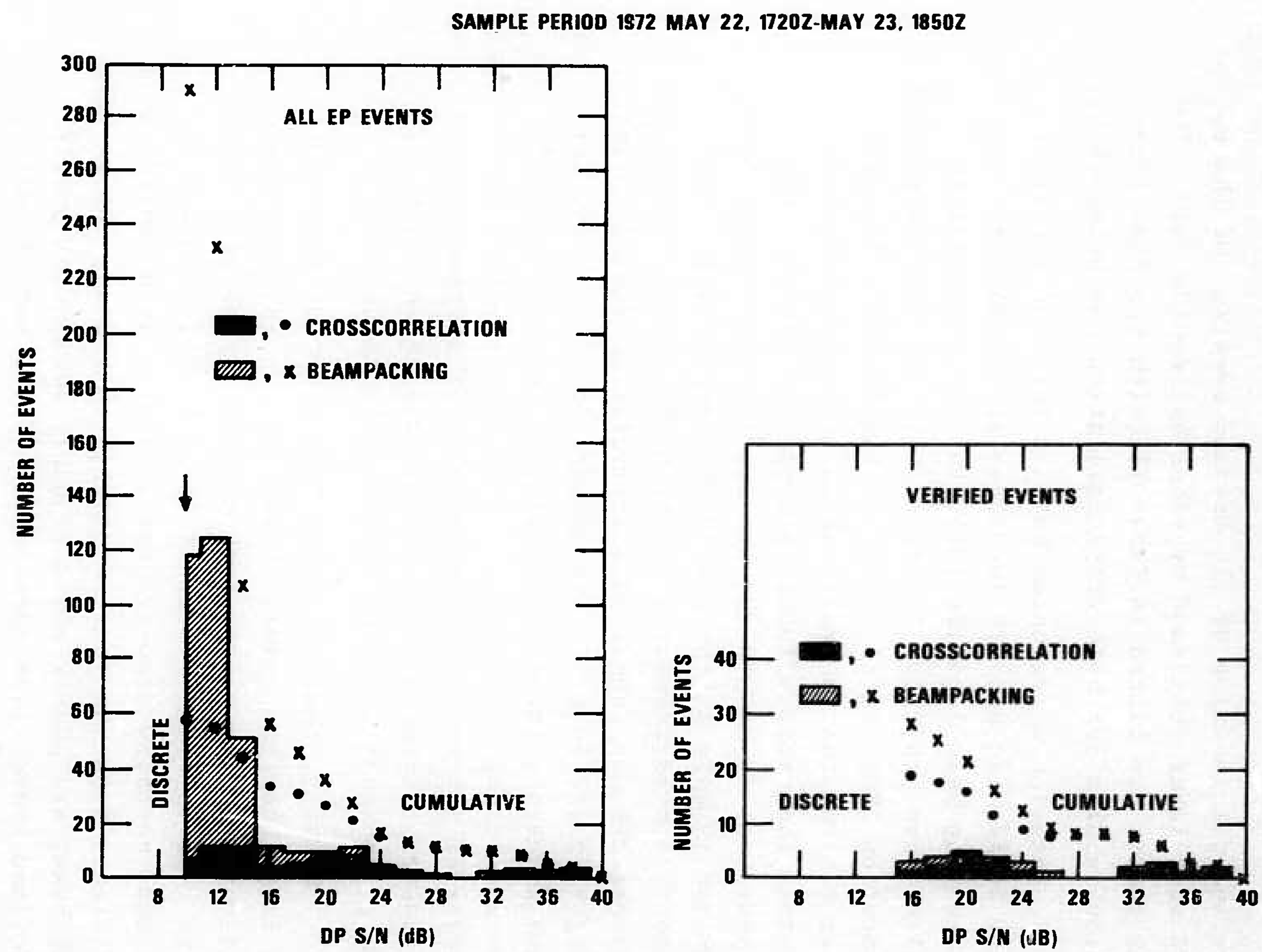

Figure 9a,b. Number of events processed to solution by Crosscorrelation and by Beampacking as a function of the DP estimate of S/N (experiment three).

refine the location of 296 assumed events. Of these, 28 were later confirmed by other World-wide data. The 28 events are listed in Table III with the SDAC location results for both crosscorrelation and beampacking.

Location differences between the SDAC locations and World-wide network locations are shown for: the detecting-beam location (DP), the crosscorrelation plane wave projected location (CC), and the beampacking location (BP). Also shown are the DP S/N's for each event. For the 18 events which crosscorrelation located, the average location error was 304 km. For these same 18 events the average location errors for DP and BP were 418 km and 436 km respectively. Two events listed were verified by NORSAR only and location errors are not shown. Crosscorrelation failed to locate eight of the events. The average location error for the 26 events located by World-wide networks is 362 km when using beampacking. This compares to a DP average error of 374 km. Thus the results of beampacking and crosscorrelation have on the average shown virtually no improvement over the detection location.

However, analysis shows that whenever DP yields a large location error, BP does also. This behavior illustrates two points both of which agree with analysis results from Experiment One. First, beampacking cannot normally recover when it starts at a considerable distance from the real location, and second, the on-line DP beams are poorly aimed probably because of poorly defined travel-time anomalies. (These same anomalies

TABLE III

List of Confirmed SDAC/LASA Events with the EP Locations and Location Errors as Compared to World-Wide-Network Locations (Experiment three).

May 1972 Day/ Arrival Time	SDAC Geographic Region Name	Cross-Correlation Lat.	Cross-Correlation Long.	Beampacking Lat.	Beampacking Long.	SDAC m_b	Distance (Deg)	Location Error (KM) DP	Location Error (KM) CC	Location Error (KM) BP	DP S/N
143/											
183155.8Z	+E. Coast Honshu	33.3N	142.0E	32.5N	141.4E	3.9	80	145	133	238	8.6:1
205828.5Z	Tonga-Fiji	16.2S	174.6W	20.1S	179.2W	6.1	90	206	178	498	75.8:1
224758.9Z	Tonga	--	--	18.5S	174.9W	4.1	89	236	--	67	11.0:1
144/											
003435.5Z	+Peru	15.2S	76.1W	15.0S	74.4W	3.8	67	121	35	180	10.5:1
004414.6Z	Mexico-Guatemala	15.0N	92.1W	29.7N	100.6W	4.6	34	1698	97	1794	20.4:1
004448.6Z	Chiapas	17.6N	94.0W	3.9N	97.0W	4.7	31	1089	290	1345	9.0:1
011526.8Z	China	38.9N	91.4E	41.5N	110.2E	4.3	93	*	*	*	7.2:1
021204.6Z	+Unimak I.	--	--	54.4N	163.9W	3.6	37	323	--	68	17.7:1
024313.9Z	+Mona Passage	24.6N	75.2W	17.7N	68.6W	4.9	42	55	1084	191	61.8:1
032648.6Z	+Greece-Bulgaria	41.6N	23.5E	41.5N	22.7E	4.7	82	258	14	78	53.2:1
034900.8Z	+Kyushu	--	--	31.2N	131.6E	3.6	87	495	--	201	6.0:1
065102.7Z	Caroline Is.	2.1N	154.0E	3.1N	155.2E	4.4	95	1323	1329	1501	13.3:1
095621.7Z	+So. Italy	--	--	39.9N	18.0E	3.6	81	180	--	150	7.5:1
100610.7Z	Azores Is.	38.4N	34.1W	38.6N	36.2W	4.3	52	317	236	413	37.3:1
101406.8Z	N. Atlantic Ocean	39.0N	35.1W	38.7N	36.4W	4.8	51	283	320	413	81.9:1
101742.3Z	Azores Is.	38.6N	34.7W	39.2N	36.2W	4.0	52	342	290	435	9.5:1
104247.9Z	+C. Kazakh	--	--	53.5N	68.6E	3.5	80	104	--	165	8.0:1
105845.6Z	N. Atlantic Ocean	--	--	39.2N	36.3W	3.9	50	395	--	469	20.2:1
111636.6Z	+So. Italy	39.1N	15.3N	39.4N	15.5E	4.1	80	147	156	145	17.2:1
120354.7Z	S. of Honshu	32.7N	140.6E	32.7N	141.1E	4.5	81	221	89	96	44.8:1
121009.5Z	+E. Coast Honshu	--	--	34.0N	141.0E	3.6	80	*	*	*	6.7:1
122552.6Z	+NW of Kuriles	47.4N	149.9E	48.2N	151.0E	3.7	65	657	89	74	10.4:1
165415.5Z	+No. Chile	22.9S	69.1W	23.2S	69.2W	5.0	77	285	63	47	44.2:1
173346.8Z	+E. Coast Honshu	33.2N	142.3E	33.2N	142.5E	4.3	79	86	33	38	13.1:1
181527.7Z	+E. Coast Honshu	33.5N	142.5E	33.8N	142.8E	5.0	79	86	19	57	45.4:1
182413.6Z	+Gulf of Alaska	--	--	59.7N	145.8W	3.8	27	100	--	126	13.1:1
182517.0Z	+E. Coast Honshu	36.7N	130.7E	35.1N	143.3E	4.0	78	197	1009	306	6.6:1
183037.0Z	Hindu Kush	**	**	35.7N	70.6E	4.9	98	**	**	313	16.8:1
				Average location error for 18 events (km)				418	304	436	
				Standard Deviation (km)				470	401	537	
				Average location error for all events (km)				374	***	362	
				Standard Deviation (km)				409		463	
				Average location error for '+' events (km)				216	248	135	
				Standard Deviation (km)				163	398	76	

+ Events from regions where the region corrections are believed to be reasonably correct.
* Confirmed by NORSAR only.
** Detected and processed by CC as PcP.
*** Crosscorrelation did not locate all events.

are used in the beampacking location process.) It should be noted that crosscorrelation not only fails on small events or events where the region corrections are known to be poorly defined but sometimes fails on large mid-range events.

Since beampacking can only refine the location of events which are detected in the main lobe of power (small DP location error), we should evaluate the location refinement capability of beampacking on only those events which satisfy this criterion. (The other events require improvements in the DP beam deployment scheme including generation of a new more complete set of region corrections.) There were 22 such events during this experiment. The average location error for these, using BP, was 217 km; for DP, it was 238 km, and for the 15 events which CC located, it was 250 km. Again all three methods show approximately the same location capability with notable individual exceptions. One further test that can be made in an attempt to evaluate the locating capability of each method is to use only those events where the region corrections are known to be good. The average errors for DP, CC, and BP then become respectively 216 km (16 events), 248 km (11 events), and 135 km (16 events). The results indicate that BP may be better on the average. The larger CC average comes mainly from two events, Mona Passage at 024313.9Z and East Coast of Honshu at 182517.0Z; however, CC did not locate five of these events at all.

Signal Size

Both beampacking and crosscorrelation arrive at essentially the same power on the final array beam. The Log_{10} A/T for crosscorrelation averaged 0.08 units higher than for beampacking, although using only those events referred to at the end of the last section, the difference is only 0.03 m_b-units.

Processing Effort

If any particular location refinement algorithm does not yield significantly better results than the others, computer processing time then becomes an important point of comparison. During this experiment, the processing of 290 events by EP using crosscorrelation required 46 hours and 24 minutes of 360/40 time. Using beampacking, the total time dropped to 36 hours and five minutes. The processing times per event are 8.60 minutes and 7.47 minutes respectively for crosscorrelation and beampacking. These time estimates include all functions of EP and not just the time required by the location refinement algorithm as discussed in Experiment One. Hence the actual savings realized by using beampacking instead of crosscorrelation is 22 percent. The EP tasks other than location refinement are: data base build from the raw data tapes, event characterization, analyst editing, and publishing which includes plot generation. These estimates are for 10db, DP and EP operation only. If EP's threshold is raised, the savings become greater

because crosscorrelation processes to completion a greater percentage of the larger events.

A savings of 22% means that up to 193 events may be processed per day instead of 150 as with crosscorrelation; in terms of S/N threshold, EP can be run at 12.6db instead of 13.3db based on the data in Figure 8.

It is important to point out that 23 percent of the 290 EP events were sidelobe detections, most of which were from events within 20 degrees of LASA. The crosscorrelation algorithm has a difficult time with the local detections and reprocesses them as many as three times. During this experiment, eight events were particularly bothersome requiring on the average 3½ hours clock time (not CPU time) to complete through the event characterization phase. A major portion of the delay is used in waiting queues, and 18-20 minutes is CPU time. Until an event has completed the characterization phase, the EP pointer cannot be moved beyond that event in the Signal Arrival Queue. This means that EP cannot re-use the space occupied by this event or any succeeding detections. In times of high activity, this problem adds a great deal of strain to the queueing system of DP and EP. Beampacking rarely reprocesses an event, normally refining the location of the energy peak detected by DP and stopping. This was alluded to in the location section above, where it was stated that beampacking could not recover from bad DP location estimates.

All the extra processing done by crosscorrelation on these events usually adds little to the final product and often totally destroys the signal.

SUMMARY

In the existing SDAC/LASA automated Event Processor, after crosscorrelation fails to complete processing an event, beampacking is used. Thirty to thirty-five percent of the Summary events studied in these experiments were added to the LASA summary by beampacking.

Most of the added events had relatively low detection S/N's, implying that crosscorrelation handles only the larger events.

However, crosscorrelation location results are not reliable. Some events with good S/N's are poorly located and some of the mislocations are not readily recognizable by visual analysis.

In regions for which the travel-time corrections are known to be good, beampacking location errors are less on the average than crosscorrelation location errors.

Beampacking cannot usually recover from poor detection locations, probably for the same reasons that caused the poor detection location.

Crosscorrelation sometimes recovers from poor detection locations but may also shift away from a good detection location.

Crosscorrelation uses approximately thirty-five percent more computer time than beampacking. Beampacking is less efficient in the use of the Central Processing Unit and hence realizes fifteen to twenty

percent savings in operational time instead of the thirty-five percent.

The EP as currently configured can handle the work load at 12db S/N for average days.

Beampacking and crosscorrelation yield array beams with comparable amplitudes on the average. The differences in the magnitude estimates are negligible.

Seventeen percent of the Summary events in these experiments were between 12db and 14db.

Twenty-three percent of the "EP events" were from sidelobes of events. Most sidelobe detections are from events occurring within 20 degrees of LASA.

Crosscorrelation has difficulty trying to resolve the sidelobe detections and often reprocesses them taking as long as 3½ hours clock-time without yielding an acceptable location.

There is no apparent degradation of the Summary when using beampacking in lieu of crosscorrelation.

Crosscorrelation generates precise delay times usable by least-squares location routines, if it is restrained to the same cycle of energy on all subarray beams.

Beampacking and crosscorrelation do no better on the average (when including all Summary events) than the DP. In the case of beampacking, the large location errors may be due to poor region corrections. With crosscorrelation, it is signal incoherence as well.

To utilize beampacking and crosscorrelation in the most effective manner, the DP location should first be refined using beampacking. If the S/N on the resulting beam is adequate, crosscorrelation should then be used to determine the delays. Crosscorrelation should be restricted to one or two iterations and two or three lags so that it cannot shift a complete cycle in alignment. The precise delays should then be used in a Geiger least-squares location algorithm to get the best possible location.

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